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Electric Propulsion Program**

D.R. Perkins

Phillips Laboratory (AFMC)

Edwards AFB, California, USA

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AN OVERVIEW OF THE AIR FORCE'S ELECTRIC PROPULSION PROGRAM

David R. Perkins*
Phillips Laboratory
Edwards AFB, California

Abstract

This paper discusses the electric propulsion technology development efforts being pursued by the United States Air Force. Discussion is provided on the electric propulsion efforts of Phillips Laboratory's Propulsion Directorate in basic research, exploratory development, as well as the Advanced Technology Transition Development effort that will result in a space flight experiment of a 26 kilowatt arcjet. Also discussed is Phillips Laboratory's ELITE/SSTAR program and a brief discussion of the Aerospace Corporation electric propulsion efforts in support of the Air Force's Space and Missile Systems Center.

Nomenclature

ATTD	Advanced Technology Transition Development
ELITE	Electric Insertion Transfer Experiment
EMI	electro-magnetic interference
EOTV	Electric Orbit Transfer Vehicle
ESEX	Electric Space Experiment
GEO	geosynchronous equatorial orbit
Isp	specific impulse
LEO	low Earth orbit
MPD	magneto-plasma-dynamic
SMC	Space and Missile Systems Center
SSI	Space Surveillance Initiative
SSTAR	Space Surveillance, Track, & Autonomous Reposition Experiment

I. Background

The Air Force has had a long standing interest in the development of electric propulsion. This has been motivated by numerous mission analysis studies that showed substantial advantages of the high specific impulse (Isp) offered by electric propulsion. Of course, the highest energy missions have shown the greatest advantages of such propulsion. Since electric propulsion tends to be a power limited technology providing fairly low thrust, applications have been constrained to space based applications. Of primary interest to the Air Force is orbit raising missions such as lifting payloads from Low Earth Orbit (LEO) to Geo-synchronous Equatorial Orbit (GEO). A electric propulsion system that performs orbit raising is referred to as an Electric Orbit Transfer Vehicle (EOTV)

II. Applications

1. Orbit Transfer

The problem with LEO to GEO orbit transfer applications of electric propulsion is that it takes very long periods of time to deliver the total impulse needed to raise a satellite's orbit to GEO, especially if power is constrained to 10 kilowatts or less. Since power is proportional to the product of Isp and thrust, higher specific impulse means lower thrust and hence even longer trip times to deliver the payload. It was for this reason that the Air Force focused much of its effort on arcjet technology since it could supply adequate thrust for orbit transfer so trip times are only several months. Additional payload advantages of higher Isp electric propulsion devices just wasn't worth the additional trip time.

The issue of trip time has recently taken on additional sensitivity in the Air Force. The Air Force Space Command became very concerned about the time required to place spacecraft on orbit with the current space transportation systems. They have stated that a launch-on-need capability be considered for the deployment of their spacecraft, and that months of transfer time might be unacceptable. The net result has been a somewhat lessened interest in electric propulsion by Space Command.

On the other hand, there continues to be a major concern at the very highest levels of the government about the cost of placing payloads into orbit. The key advantage of electric propulsion for orbit raising is that its very high Isp would allow the possibility of manifesting spacecraft on smaller and less expensive spacecraft. For example, a payload destined for GEO could be remanifested off of a Titan IV launch vehicle that costs in the neighborhood of \$200 million and placed onto an advanced Atlas that costs roughly \$100 million. This is a powerful argument as to why electric propulsion still is considered for orbit raising, despite the concerns about trip time.

2. Station Keeping and Maneuvering

A very important lesson was learned during the Persian Gulf conflict. Modern military operations can take substantial advantage of spacebased assets. However, those assets are not necessarily located in orbits that can support those operations. To reposition those satellites takes time

* Senior Advanced Propulsion Engineer, Member AIAA

and propellant that was intended for on-orbit station keeping. This results in substantial loss of on-orbit life of a repositioned spacecraft. The lesson is that if we wish to use satellites to support regional conflicts whose location cannot be predicted beforehand, then more on-orbit maneuvering and stationkeeping propulsion capability is desirable.

Classical chemical satellite propulsion systems cannot supply this capability without large mass penalties that have huge cost penalties. Since the thrust requirements for station keeping are very low, electric propulsion appears to be particularly well suited for this role.

There appears to be an ironic advantage for electric propulsion's low thrust in orbital repositioning. Chemical propulsion systems are of such high thrust that the impulse required for orbit repositioning is delivered in very short times. Most of the repositioning time is constrained by the physical limitations of orbital mechanics. To significantly shorten the repositioning time requires significantly more propellant to be expended and/or to perform many short duration burns. On the other hand, electric propulsion is of such a low thrust that kinematic considerations seem to dominate the orbit repositioning, such that the satellite repositioning maneuver is accomplished in significantly shorter periods of time.

III. Phillips Laboratory's Propulsion Directorate

1. Facility

Phillips Laboratory has established an electric propulsion laboratory at its Propulsion Directorate at Edwards AFB, California. This laboratory is currently manned by seven scientists and engineers. The facility has been developed to primarily investigate high power arcjet thrusters^{1,3}, but has been used to investigate MPD thrusters² and is also used to evaluate other related technology issues.

The principal features of the facility are three vacuum chambers of moderate size that are designed to handle relatively high mass flow rates associated with arcjets by using relatively large mechanical roughing pumps. One chamber that has been used extensively for magneto-plasma-dynamic (MPD) thruster testing has diffusion pumps to draw the deeper vacuums required by those thrusters. Two of the chambers have water cooling to handle the heat generated by the high power arcjets. The facility has a 800 kilovolt-ampere service that supports testing. The presence of significant support services greatly enhances development activity.

2. Basic Research

The basic research effort being performing at Phillips Lab is sponsored by the Air Force Office of Scientific Research (AFOSR). The in-house effort has been enabled by the buildup of a vacuum chamber specifically designed for optical diagnostics. We have procured a laser induced

fluorescence system, a high resolution imaging system, an optical pyrometer system, and a time resolved emission spectroscopy system.

An area of current activity is a joint effort with the University of Southern California, the University of Tennessee Space Institute, and the University of Texas to develop nonintrusive diagnostic techniques to investigate energy losses in plasma thrusters^{4,5}. This is motivated by the relatively low efficiency in arcjets. The approach is to investigate frozen flow losses, viscous losses, and fundamental energy transport mechanisms. The goal is to improve plasma thruster efficiency from 30% to 50%, and/or improve specific impulse by 20%.

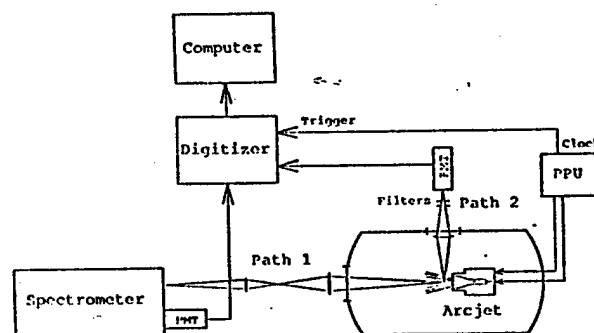


Fig. 1. Experimental Setup of the Arcjet/PPU Interaction Study.

Another area of interest that is being explored with the University of Southern California is the effect of high frequency switching on the operation of an arcjet. Power supply current ripple effects arcjet operation in a number of ways. Electron emission fluctuation of the cathode might be experienced. Anode arc attachment varies. This introduces propellant turbulence due to thermal-hydraulic variations, thus causing boundary layer growth. Additionally, due to arc/propellant energy transport fluctuations, frozen flow losses vary. The experimental setup shown in figure 1 has been established, and plume emission intensity variations noted in figure 2 have been observed in the alpha hydrogen line. This implies excited state frozen flow variation. It is interesting to note that momentum of the exhaust stream is not observed to fluctuate.

The research program is beginning an effort to correlate the results of plume transport models with the energy transport models being developed for arcjets. A key step is to use the results of the Electric Space Experiment (ESEX) to normalize and validate these models.

3. Exploratory Development

Exploratory development activities have been primarily focused on in understanding life limiting mechanisms of arcjets, although some effort was spent on MPD thruster technology also.

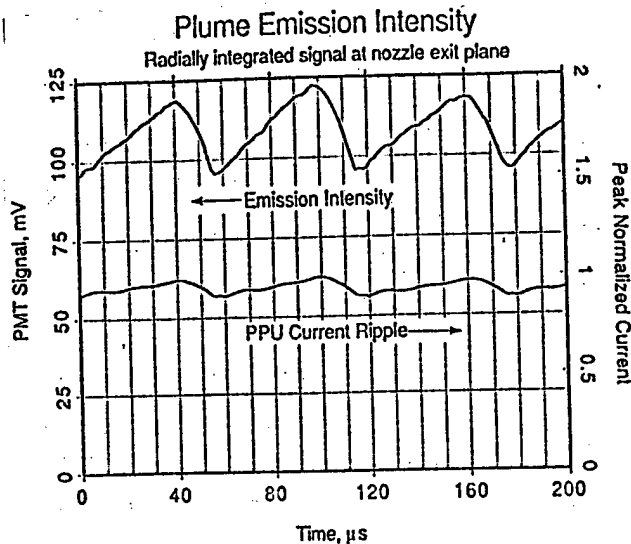


Fig. 2. Results of Arcjet/PPU Interaction Study.

The primary area of effort here is in the experimental evaluation of the start phenomenon of an arcjet^{6,7}. The objective of this effort has been to identify the physical mechanisms which affect propellant breakdown in an arcjet. A model was developed which can quantitatively predict the phenomenon associated with propellant breakdown in an arcjet. This model, and experimental data that was obtained, were essential for the design of the start circuit for the 26 kilowatt ammonia arcjet to be used on the ESEX flight experiment. Figure 3 shows an overlay of the experimental results in a 1 kilowatt arcjet with the theoretical models.

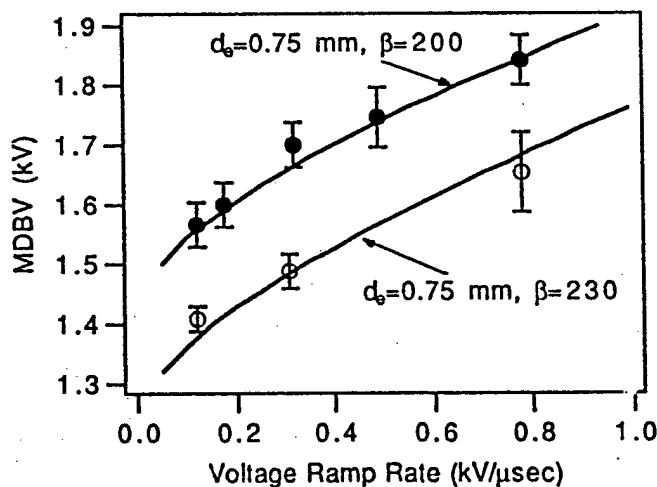


Fig. 3. Results of start phenomenon testing.

Another area of study is the use of radio frequency start circuits for arcjets. The goal of this effort is to overcome the issue of very high start voltages required of direct current start circuits. The principal concern is the mass of series isolation inductors for the high power arcjets.

One long term effort is the development of arcjet computational models to assist in the development of

arcjet thrusters. One model is for arcjet nozzles. It is intended to answer sensitivity of performance to nozzle geometry. Traditional nozzle models are inadequate due the extreme variation in gas outlet temperatures. Coupled to this effort is a general arcjet performance model that would accurately predict the flow conditions (temperature, flow velocity, chemical species, etc.) within an arcjet. Another model that supports the arcjet start phenomenon testing is an arcjet internal electric field model. It identifies peak cathode surface electric fields. There has also been work to develop a collisional-radiative model that is needed to relate experimental diagnostics data acquired in the basic research effort.

4. MPD Efforts

There has been a long term interest in magneto-plasma-dynamic (MPD) on the part of the Air Force. We have been primarily interested in the self generated magnetic field concepts that would be attractive for high power steady state applications. Due to the failure of any significant high power space power programs to get off the ground, we have greatly decreased the level of effort we are expending in this area. The big advantage of MPD thrusters is very high thrust density in a relatively simple design that can supply very high specific impulse (on the order of 3000 seconds).

4.4 kA, 0.5 g/sec

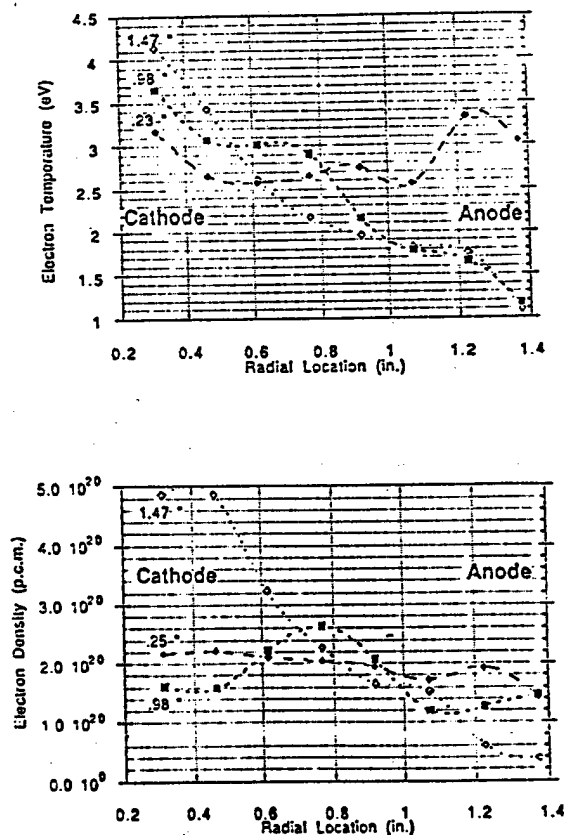


Fig. 4. Internal measurements of MPD electron temperature and number density.

The effort that has been ongoing has been in cooperation with Purdue and MIT. The Purdue effort investigated micro-instabilities⁸ in the interior of the MPD thruster. The MIT effort extensively mapped plasma properties inside the thruster. Figure 4 shows some sample results of that effort.

5. Small Business Innovative Research Efforts

A phase II small business innovative research effort (SBIR) is currently on-going with the Electric Propulsion Laboratory of Monument, Colorado⁹. This effort is investigating geometry variations of an arcjet constrictor to achieve performance enhancement.

In the last several months, there have been 10 phase I SBIR contracts awarded by the Propulsion Directorate in the electric propulsion area. Three awards are to investigate methane arcjet designs. Three are intended to evaluate advanced insulators for arcjets. Four are evaluating methods on increasing the emissivity of arcjets.

6. Electric Space Experiment (ESEX)

The dominant effort from a funding perspective has been the 30 kilowatt advanced technology transition development effort^{10,11}. The principal product from this activity is the ESEX (see figure 5) space flight package that is to be integrated into the Advanced Research Global Observation Satellite (ARGOS), which is also known as the P91-1 spacecraft. The ESEX contractor is TRW, and they are scheduled to deliver the experiment in August of 1994. The ARGOS spacecraft is being assembled by Rockwell International for the Air Force's Space and Missile Systems Center (SMC). ARGOS (see figure 6) integrates several space flight experiments onto a single spacecraft bus for SMC's Space Test and Small Launch Vehicle Programs Office. It is scheduled for launch in October 1995 on a Delta II launch vehicle.

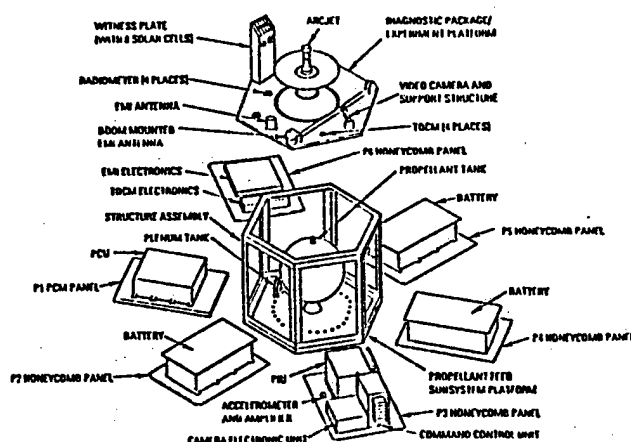


Fig. 5. ESEX.

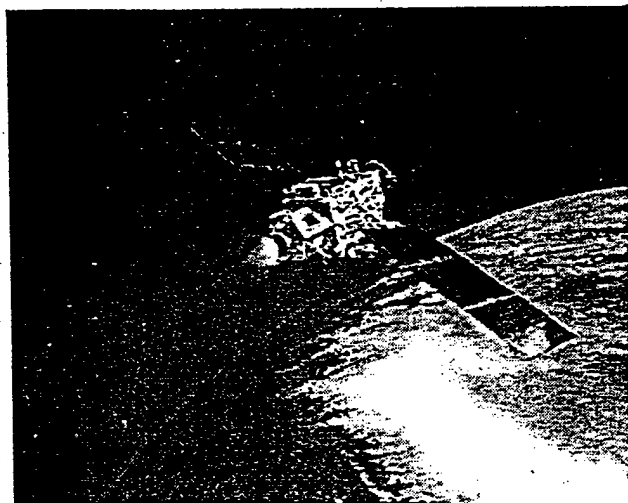


Fig. 6. ARGOS.

ESEX is a fully integrated ammonia arcjet propulsion system. It includes the thruster, a propellant feed system, a power controller, batteries for energy storage, associated flight software, and a complete diagnostics package. The diagnostics package¹² will supply information about electro-magnetic interference (EMI), plume contamination, and visible plume characteristics.

Since ARGOS has limited power capability, ESEX will have an experimental duty cycle of 24 hours for battery charging followed by a 15 minute burn with the arcjet operating at 26 kilowatts¹³. Ten of these cycles are planned. It will be possible to obtain performance information based on actual spacecraft orbit changes.

7. Advanced Technology Development Testing

The electric propulsion lab at Edwards AFB has performed two key tests directly addressing problems critical to both ESEX and ELITE (described below). The first of these was a ground evaluation of the EMI generated by a high power arcjet. The second was the simulation of a complete power train from a solar array, through a peak power tracker, the power processing unit, and finally to the thruster.

The EMI experiment^{14,17} was requested by the SMC community as a means of reducing concern that this was a significant issue. It was a cooperative venture involving personnel from SMC, the Aerospace Corporation, TRW, and Phillips lab. It required some innovation to perform the test. EMI testing of a high power arcjet operating in a metallic vacuum chamber was challenging. Basically, an anechoic chamber was built inside one of the vacuum chambers. Good results were finally achieved with the use of insulated antennas. Results indicated that although the EMI levels were significant, they did not pose a significant risk to spacecraft electronics and communications equipment.

The spacecraft power system end-to-end tests¹⁵ were very enlightening. Sponsored by the ELITE program, the tests showed that basic solar array power supply fluctuations were an important consideration in designing filters for the power conditioning units. The tests were performed by TRW and Phillips Lab personnel using a power processor supplied by NASA's Lewis Research Center. The next phase of this effort is to incorporate an ion engine and evaluate its operation with the power train. Since the facilities at NASA Jet Propulsion Laboratory are better suited for ion engine testing, the tests have been moved there.

IV. SSTAR/ELITE Program

The Phillips Laboratory's Space Experiments Directorate has been working on a cooperative research and development effort with TRW to demonstrate key technologies required for an EOTV. The effort, known as the Electric Insertion Transfer Experiment (ELITE) is intended to integrate and validate several key technologies that are required for an EOTV. These include long life thrusters, power supplies that can survive extended periods in the Van Allen radiation belts, and autonomous guidance, navigation and control.

The effort, as currently envisioned, would integrate two arcjets and an ion engine on a thruster platform. It would be powered by a ten kilowatt solar array. The orbit would be raised to about kilometers altitude. TRW is developing the spacecraft bus, the guidance navigation and control, and the propellant feed system. They are also taking responsibility for spacecraft integration. Phillips Lab is responsible for the thrusters, solar arrays, and the diagnostics package.

ELITE is now being merged with the Space Surveillance Initiative (SSI) because the ELITE spacecraft would serve as an outstanding bus for this experimental initiative. The combined ELITE/SSI spacecraft has become known as the Space Surveillance, Track and Autonomous Reposition (SSTAR) program¹⁶. Current plans call for a launch of the spacecraft on a Titan IIG launch vehicle in late 1997.

V. SMC Sponsored Aerospace Corporation Efforts

1. UK-10 Engine Evaluation

The Aerospace Corporation's Electric Propulsion Laboratory in El Segundo, California, is currently performing a "Foreign Comparative Test" program of the British UK-10 ion thruster (See Figure 7). This work is being performed for the Air Force's Space and Missile Systems Center. The Aerospace Corporation test program is aimed at the determination of spacecraft integration risks that have not been adequately determined before.

The interest in this thruster is primarily generated by the Air Force in applying this technology to North-South station keeping of geosynchronous satellites such as the

Defense Satellite Communications System. The UK-10 and Germany's RIT-10 thruster systems have been selected for the ARTEMIS (Advanced Relay and Technology Mission) technology demonstration satellite scheduled for an early 1996 launch.

The Aerospace program is scheduled to proceed through fiscal year 1994. An extensive list of diagnostic tests are planned. They include evaluation of the performance envelope, near field plume characteristics, laser-based spectroscopy, mass spectroscopy, electro-magnetic interference, and contamination.

2. EOTV Studies

The Aerospace Corporation completed an extensive general systems engineering and integration study¹⁸ of electric propulsion for orbit transfer vehicle applications. Trade analyses were performed on performance, weight, specific power, specific impulse, thruster efficiencies, transfer time, navigation errors, steering accuracy, solar array aspect ratio, and array degradation. Specific impulse from 700 to 4000 seconds was considered.

Findings suggested that large steering errors are acceptable; gimbaled thrusters are feasible; solar array degradation, shadowing, and imperfect array pointing affects transfer time and not propellant consumption; and solar array aspect ratio shielding requirements have a large impact on control torques.

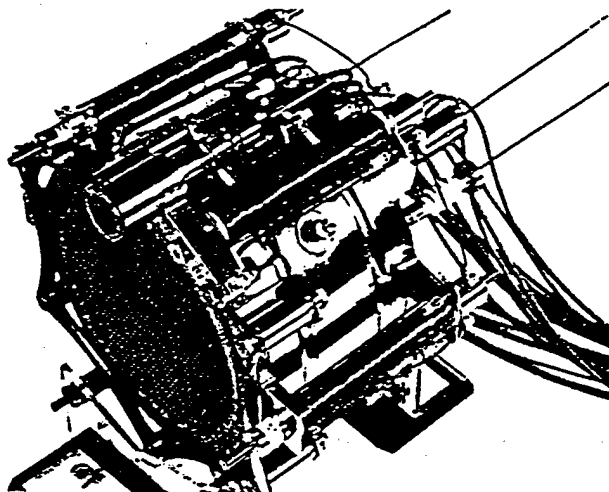


Fig. 7. UK-10 thruster with the earthed screen removed.

Regarding thrusters, the study found that a hydrogen arcjet has significant performance advantages compared to an ammonia arcjet, and requires less power for a given transfer time than ion engines. The efficiency of the propulsion subsystem, at a given specific impulse, and the specific power of the electrical power subsystem are dominant factors affecting trip time.

Conclusion

Electric propulsion continues to offer significant space mission advantages. As the technology is matured and the transition of the technology is pursued, there will arise more pragmatic consideration of technology investment needs such as enhanced reliability and life. It is the cooperation of government and industry that will successfully transition this technology to the broadest number of users. Industry, through their use of this technology in commercial spacecraft, and their proposal to use it in future DoD and NASA satellites, does much to convince high level decision makers of the need for electric propulsion. The government, on the other hand, must validate the readiness of the technology to be transitioned into space systems and perform an essential service of fairly evaluating the technology. We at Phillips Laboratory are anxious to continue developing a strong relationship with industry that will lead to successful transition of this technology into far more capable and cost effective space systems of the future.

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